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Where is global waste management heading? An analysis of solid waste sector commitments from nationally-determined contributions

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ABSTRACT

Waste-sector greenhouse gas emissions have long been accepted as a critical component of climate change mitigation efforts because of the significant radiative forcing of methane (CH_4) production from municipal landfills and other emissions from waste management processes. In developed countries, waste generation is expected to peak and decline by the end of the century, whereas waste generation is rapidly rising in many developing nations. The extent to which the countries of the world are planning to handle future quantities of waste has not been explored in detail. This work provides the first detailed account of future waste management planning and waste-sector mitigation strategies through an analysis of stated commitments in the 174 Nationally Determined Contributions (NDCs, documents outlining each country's actions to mitigate carbon emissions and adapt to a changing climate) that have been filed to date within the Framework Convention on Climate Change secretariat in Bonn. One-hundred thirty-seven of 174 countries that submitted NDCs included waste-sector emission mitigation actions, representing approximately 85% of all global emissions. About half (67) of the countries that included waste sector mitigation tactics identified infrastructure or policy actions to meet mitigation commitments, but these strategies vary widely in their scope and level of detail. Landfilling was the most commonly-cited waste-sector commitment (n = 47), followed by deriving energy from waste through various techniques (n = 42). Countries targeting improved solid waste collections had less extensive coverage ($\mu_{collection}$ = 38% of generated waste collected) than countries that did not prioritize improved collections ($\mu_{collection}$ = 46% of waste generation), but countries not prioritizing the waste sector at all in NDCs had the most limited waste collection coverage ($\mu_{collection}$ = 33%). Almost all of the countries that specified emissions inventory assumptions (132 of 135) use outdated CH_4 global warming potential values which, coupled with missing or poor waste management data suggests many countries may be underestimating the importance of waste sector emissions in national emissions portfolios. Several examples of data collection and reporting models are identified that can help to inform and potentially improve life-cycle environmental outcomes in the waste sector. Adaptation strategies detailed in NDCs have largely overlooked the waste sector, suggesting inadequate incorporation of future climate scenarios in waste sector infrastructure planning.

1. Introduction

The United Nations Framework Convention on Climate Change (UNFCCC) adopted a goal in 2015 to limit further global warming to 2 °C above pre-industrial levels as part of the 21st Conference of the Parties (COP 21). COP 21 culminated in the Paris Climate Agreement, an historic accord that, for the first time, aligned nations toward the common goal of combating climate change and adapting to its impacts (UN Framework Convention on Climate Change, 2015b). To help achieve the stated global warming goal, parties to the Paris Climate Agreement developed Intended Nationally Determined Contributions, referred to as Nationally Determined Contributions (NDCs) following submission. These NDCs tailor broad emission mitigation goals and climate change adaptation plans to the country's specific context by accounting for national priorities, technical and economic capabilities, and relative responsibility for action (Table 1) (World Resources Institute, 2016).

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Table 1
Elements commonly included in country-level NDCs prepared in advance of the Paris Climate Agreement.

NDC element	Description
Introduction and national circumstances	Overview of basic information about the country (population, size, major industries) May include qualitative description of current or historical contribution to climate change and anticipated effects or vulnerabilities of future climate change
Emissions profile	May include historical, current, and/or projected future emissions, presented in aggregate or as the sum of individual climate-forcing pollutants
Mitigation plans and potential	The country's mitigation goals, presented as an anticipated outcome (e.g., a percentage reduction of GHG compared to some baseline), a series of mitigation actions (e.g., GHG-emitting sectors of focus, GHGs of focus), or a combination of the two Targeted sectors commonly include agriculture, buildings, energy efficiency, forestry, renewable energy, transportation, and waste
Adaptation	Establishing the country's need for adaptation and plans to address it
Financing	A discussion of financing plans or other resource mobilization strategies

Greenhouse gas (GHG) emissions from the waste sector represent one of the largest non-CO_2 sources (IPCC, 2013) globally. Although a range of human health environmental consequences can result from waste management (Giusti, 2009; Seadon, 2006), climate-related emissions from waste principally consist of CH_4 emissions from landfills. The magnitude of CH_4 emissions demands action to limit GHG-caused radiative forcing in the short term (Tian et al., 2016). At longer time scales, mitigating waste-sector emissions represents an important "wedge" for stabilizing carbon emissions globally (Pacala and Socolow, 2004) to reduce warming and climate-induced effects such as sea-level rise (Zickfeld et al., 2017).

Increasing population in many countries and accelerated urbanization, particularly in lower- and lower-middle income nations, are expected to increase global waste production for several decades (Hoornweg et al., 2013, 2015). Urbanization may also directly contribute to atmospheric warming (Sun et al., 2016). Additions to building stock and the production or import of materials both have substantial impacts on waste generation, particularly in megacities – those with a population greater than 10 million – which are projected to grow in number from 23 (2010) to 41 by 2030 (United Nations, 2014). While the magnitude of waste production rates in megacities varies depending on the level of infrastructure development and individual consumption, waste production rates in megacities are often far higher than per-capita global averages (Kennedy et al., 2015). Similarly, waste management across the world occurs on a continuum, with disparate challenges spanning financial capacity, technical capacity, and infrastructure. Demographic and economic variables also shape waste quantities and composition, which in turn dictates the technical approaches used to safely handle waste (Barton et al., 2008; Karak et al., 2012; UNEP, 2015).

Previous assessments of global waste management have principally focused on historical management (Karak et al., 2012), current technological practices (UNEP, 2015), or future estimates of waste quantities (World Bank, 2012). The UNFCCC conducted a high-level analysis of NDCs (UNFCCC, 2015b), but the only relevant waste-sector detail indicated the number of countries with a waste-related commitment. Here, the NDCs are examined and the specifics of country-level waste-sector mitigation actions are catalogued and analyzed, representing the first detailed account of how most of the world will be managing waste in the future. This analysis can provide an important baseline against which future updates to NDCs, which are required to occur every five years under the Paris Climate Agreement's provisions, may be compared. The common formatting structure of NDCs enables a previously-unavailable analytical framework which, coupled with emerging data and measurement systems in the waste sector, can be used to bolster the tracking of waste-sector carbon emission mitigation actions.

2. Materials and methods

2.1. Data from Nationally Determined Contributions

Each nation's NDC was downloaded from the UNFCCC website (UN Framework Convention on Climate Change, 2017) in March 2017. The English-language version of each NDC was reviewed where available, and non-English language NDCs were translated into English prior to review. Each NDC was searched to identify whether mitigation or adaptation plans included the waste sector. Because many countries did not explicitly indicate which commitments were conditional (i.e., commitment contingent on additional funding or resources) or unconditional (i.e., a commitment to be executed independent of outside funding), the commitments were reviewed together.

Waste sector actions were examined by reviewing each NDC and extracting specifically-stated planned actions, such as improving landfilling or diverting organic materials. All specific actions and commitments were extracted and indexed to each country in a spreadsheet program. Each action was tabulated, then five groups were created to reflect the most commonly-cited actions (improved collection, composting, recycling, energy from waste, and improved landfilling).

2.2. Analysis of Country-level waste collection and improvement strategies

Country-level waste collection levels were calculated from previously-published data (Wiedinmyer et al., 2014) as the difference between reported mass of waste generated and mass of waste uncollected (year 2010 values) as shown in Eq. (1).

$$M_{Collected,i} = M_{Generated,i} - M_{Uncollected,i} \tag{1}$$

Here $M_{Collected,i}$ is the mass of waste collected in country i (Mg), $M_{Generated,i}$ is the mass of waste generated collected in country i (Mg), and $M_{Uncollected,i}$ is the mass of waste uncollected in country i (Mg). The waste collection rate (CR) for country i was then computed as shown in Eq. (2).

$$CR_i = \frac{M_{Collected,i}}{M_{Generated,i}} \tag{2}$$

2.3. Country-level non-CO_2 GHG emissions and waste data

Although many NDCs provided an estimate of total GHG emissions, most did not provide sector-by-sector emission estimates. Furthermore, many countries utilized different global warming potential (GWP) values and baseline years in the GHG emission communications – as allowed under NDC development guidelines – which limited direct comparisons. The U.S. Environmental Protection Agency was sourced to establish a consistent baseline for comparison, non-CO_2 emissions data – these data are also presented in the Supplementary Information (U.S. Environmental Protection Agency, 2013). The total non-CO_2 emissions profile and the waste sector emissions were matched with each country with an NDC for further analysis.

In the GWP analysis, the country-GWP match was combined with the waste-sector non-CO_2 emissions data from the

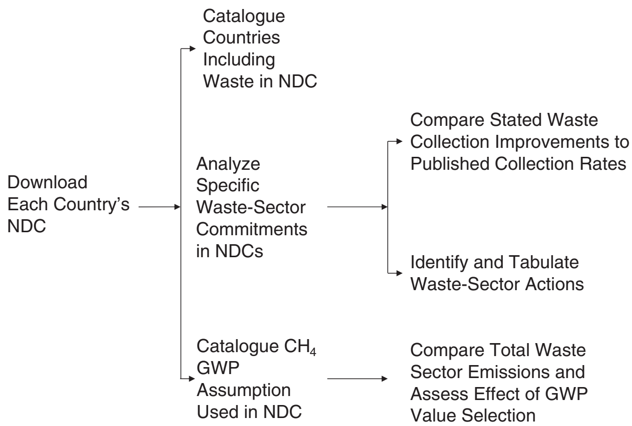

Fig. 1. Methodological framework used to analyze NDCs.

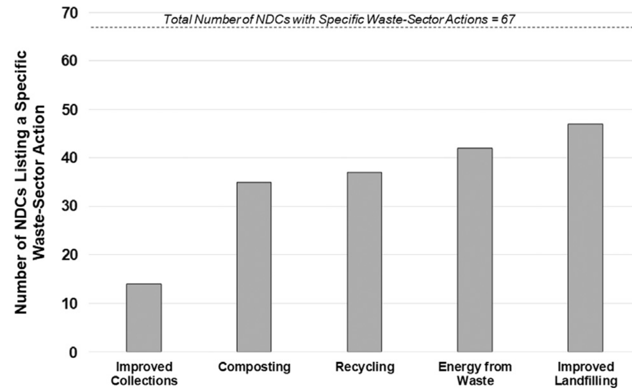

Fig. 3. Number of specific waste-sector mitigation actions listed in NDCs. Commitments in countries specifying waste-sector actions were analyzed to identify specific activities that each country is planning.

U.S. Environmental Protection Agency (2013) to examine the share of non-CO_2 emissions comprised by the waste sector in each country. Although the U.S. Environmental Protection Agency data reflect emissions from solid waste management and wastewater, the solid waste management portion generally represents majority of waste sector emissions and thus the CH_4-focused GWP analysis still holds. The share of waste-sector emission contributions was calculated as a ratio of total waste-sector GHG emissions and the total non-CO_2 GHG emissions for each country. Quarter-increment bins (i.e., 0–25%, 26–50%, 51–75%, and 76–100%) were developed and the data from each country were grouped according to the fractional share of waste sector emissions. The difference in total non-CO_2 emissions in each country was calculated by adjusting the CH_4 GWP to the current value of 28 and re-estimating the share of the waste-sector GHG emissions as part of the total non-CO_2 emissions. Fig. 1 summarizes the analytical framework described in Sections 2.1, 2.2, and 2.3.

3. Results and discussion

3.1. Waste-sector commitments in Nationally Determined Contributions

NDCs representing 174 countries accounting for 1339 million Mg of CO_2-eq or 91% of 2010 global waste sector emissions were reviewed, of which 137 countries had a broadly-stated waste sector mitigation commitment, covering 1246 million Mg CO_2-eq or 85% of global waste sector emissions. Fig. 2 displays the geographic distribution of countries that did or did not submit waste-sector commitments in NDCs.

Only 67 of the 137 NDCs cited at least one specific waste sector action toward future mitigation. Fig. 3 summarizes the frequency of each type of waste-sector mitigation commitment listed in the NDCs. Improved landfilling – which may include closing or rehabilitating old waste disposal sites, developing new sanitary landfills, or enhancing existing landfills – was the most commonly-cited mitigation action (n = 47). These results are broadly consistent with previous observations that landfills are and will continue to be a key part of waste infrastructure in the near term, especially in developing nations (Powell et al., 2016). Energy recovery from waste (n = 42), which includes waste processing (e.g., incineration) and landfill gas-to-energy projects, was the second-most prioritized waste sector action. The high frequency of energy recovery efforts may stem in part from relatively quick potential carbon emission reductions and economic returns relative to other approaches such as composting (Couth, 2012).

Despite previous global reviews of waste management that highlight the severe shortages in waste collection coverage (World Bank, 2012), NDCs included limited mention of improved

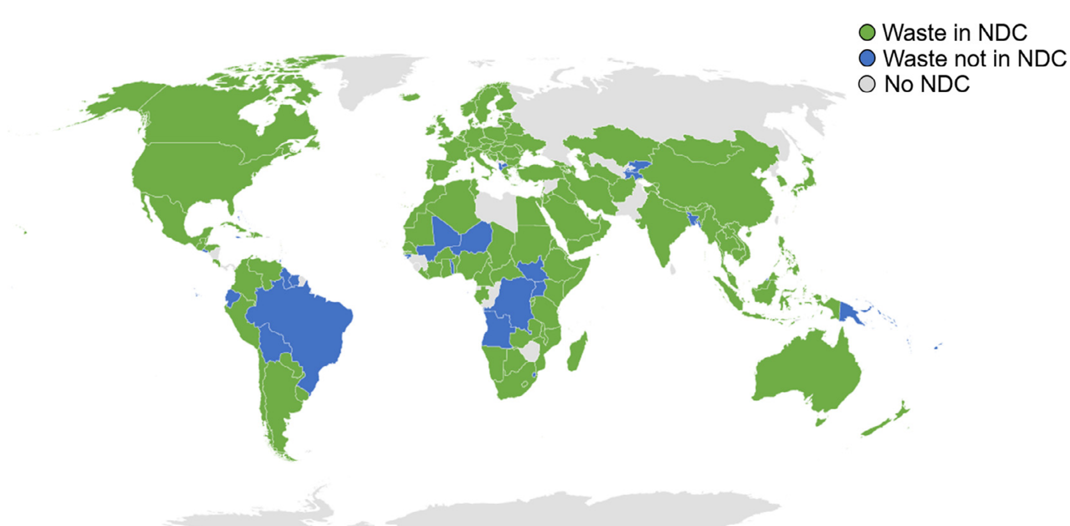

Fig. 2. World map of waste-sector commitments in NDCs. The map displays countries that mentioned waste as a sector to focus carbon emission mitigation efforts, countries that submitted an NDC but did not mention waste, and countries for which NDCs were not prepared.

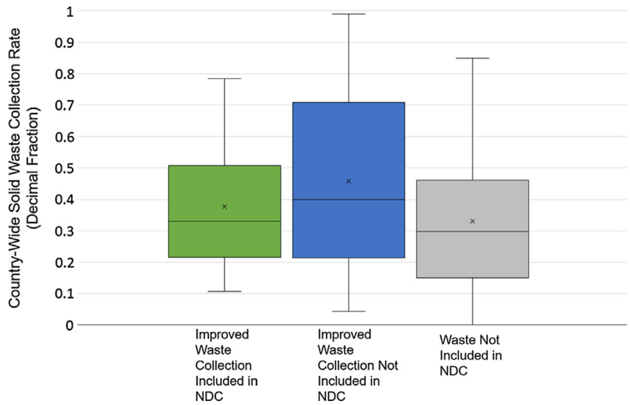

Fig. 4. Comparison of formal waste collection coverage in countries with and without waste-sector GHG emissions mitigation plans in NDCs. The line in the box represents the median value, the "x" represents the mean, the box extents are the 25th and 75th percentiles, and the whiskers are the 10th and 90th percentiles. Countries that include the waste sector in mitigation plans and specifically target improving collections (n = 14), those including the waste sector in mitigation plans but no specific mention of improving collections (n = 79), and those not including waste in the NDC (n = 37) are shown.

collections in future mitigation plans. Countries that mentioned waste in the NDCs were analyzed to assess the relative collection system coverage, and the results are shown in Fig. 4. Fig. 4 shows that the waste collection coverage of those aspiring to improve collections (mean = x, median = x) was less than those who did not target collections in waste sector mitigation plans. The group with the lowest collection rate was observed in countries that did not mention waste as a mitigation sector focus area (mean = x, median = y). Although collection coverage data are not static and may be expected to have inherent error because of the difficulty in measuring collection coverage, these results support the idea that the decisions to target improved collections are broadly consistent with the Paris Climate Agreement goals of using measurement to drive decisions.

The data in Fig. 3 suggest that many countries are at the early stages of developing waste recycling and disposal schemes, which contrasts to previous assessments that suggested many nations are locked into their current waste management infrastructure for years to come (Hoornweg et al., 2015). Because new infrastructure and systems to handle waste will need to be developed, a global opportunity exists through the NDC commitments and subsequent actions to substantially reduce GHG emissions in the waste sector on both short- and long-term time scales. Emission reduction actions were found to mostly include those that directly reduce emissions, but waste reduction and prevention efforts can further decrease emissions and should be considered as NDCs are modified in the future. Using integrated tools such as technology assessment models, including those that incorporate the life cycle of waste materials and processes (Hellweg and Milà i Canals, 2014), will be critical to identify the mix of technical and economic options that optimize net CO_2 emission outcomes (Andreasi Bassi et al., 2017) as nations seek reductions in carbon emissions across multiple sectors. Using high-quality, country- and context-specific data to inform life-cycle models (and therefore waste infrastructure planning) carries a great deal of importance because optimizing GHG emissions can conflict with traditional waste hierarchies when broader systems are considered (Arena and Di Gregorio, 2014). Rapidly-changing economics and regulatory factors may also influence the relative cost and magnitude of emission reductions, such as that observed in recent studies evaluating energy production from combustion and landfill gas utilization in China (Wang et al., 2016).

3.2. Reviewing global warming potential assumptions

Most of the NDCs laid out methodological assumptions that justified sector inclusion within mitigation plans, including the GWP of non-CO_2 GHG,. Because CH_4 has a radiative forcing strength many times that of CO_2, and the GWP for CH_4 has increased over time as the magnitude of its warming ability is better understood, the waste sector represents a more significant short-term climate change mitigation component than has been previously appreciated. The 2013 Intergovernmental Panel on Climate Change (IPCC) report suggests that the GWP for CH_4 is 84 on a 20-year time horizon and 28 on a 100-year time horizon – far greater than the respective previous values of 56 and 21 from 1996 (IPCC, 2013). Because the GWP value directly impacts the total GHG emission estimates for each sector (though not the absolute mass emissions of CH_4), the GWP selected can therefore strongly influence a country's decision to include a given sector in its NDC (World Resources Institute, 2016). Given the evolution of the CH_4 GWP over time, the distribution of GWP assumptions made by each county were analyzed to quantify each country's use of contemporary GWP values.

Table 2 summarizes the results of the NDC GWP review. Of the 135 instances where a country listed a GWP assumption, 132 use the 1996 or 2006 IPCC 100-year GWP values for CH_4 (21 and 25, respectively). These 132 countries employing an outdated CH_4 GWP value represent 84% of global waste-sector emissions (year 2010 estimate).

Fig. 5 shows the distribution of countries using a 100-year CH_4 GWP of 21 or 25 to portray how significant the waste sector emissions are compared to other non-CO_2 GHGs. The figure reveals that waste comprises less than 25% of national non-CO_2 emissions (year 2010) in 90 of 135 countries. The remaining 45 countries, which comprise 29% of global waste sector emissions, individually show more than 25% of their non-CO_2 emissions originating from the waste sector. When adjusting 2010 waste-sector and total non-CO_2 emissions to reflect the current CH_4 GWP of 28 rather than

Table 2
Total waste-sector emissions (Year 2010) by countries using different GWP values in NDC country reports.

GWP value used	Number of countries	Sum of waste-sector emissions (Year 2010, 10^6 Mg CO_2-equivalents)	Percentage of total non-CO_2 emissions from the waste sector (%)
21	57	216	21.9
25	75	617	62.6
28	3	152	15.5
Totals	135	985	100.0

Note: Emission totals may not sum evenly due to rounding.

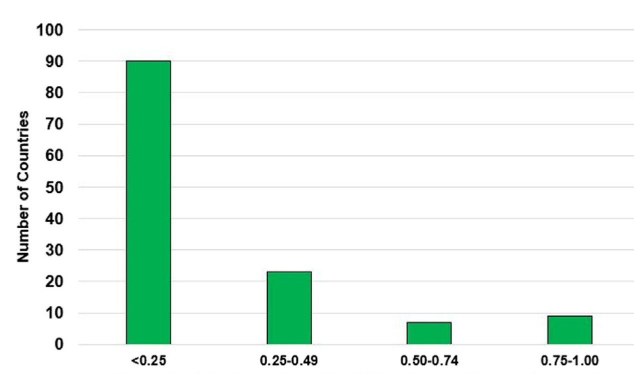

Fig. 5. Number of countries using a CH_4 GWP of 21 or 25 in NDCs and the fraction of non-CO_2 GHG emissions from the waste sector.

21, more than half (56%) of countries that listed a GWP showed at least a 3% increase in total non-CO_2 emissions from the increased waste sector contribution alone (median = 3.9% ±2.1% S.D.). The results further show an approximately 17% increase from 828 million Mg CO_2-eq to 972 million Mg CO_2-eq when considering similar impacts for all waste-sector emissions.

The large number of nations with a substantial portion of non-CO_2 emissions from waste, coupled with the widespread use of lower GWP values for CH_4 suggests that countries may be underestimating the contribution of the waste sector to their national emissions portfolio. Further, the lack of high-quality waste data in many countries and well-documented limitations of top-down waste generation estimates (Bogner et al., 2008; Hoornweg et al., 2015; Powell et al., 2016; UNEP, 2015)increases the likelihood of underestimating emissions mitigation. These observations suggest that nations are currently undervaluing the potential of a robust waste-sector emissions mitigation strategy.

3.3. Data collection and reporting systems

More than half of the NDCs emphasize developing MRV systems to establish baseline emissions and to track future emissions across sectors more rigorously. Historically, obtaining high-quality waste data has been challenging in most countries (UNEP, 2015), but new examples leveraging web-based technologies (Eurostat in the European Union (Eurostat, 2018) and the GHG Reporting Program in the United States (US Environmental Protection Agency, 2018)) emerged in recent years. These repositories for waste informatics, which detail key information such as waste disposal rates, CH_4 collection efficiencies, and facility locations, can be coupled with comprehensive waste-focused life-cycle analysis models (Christensen et al., 2007; Gentil et al., 2010; Levis et al., 2014) to expand the quality, amount, and analytical rigor of waste data to support decision making worldwide. In addition to using emerging data systems, efforts such as those from the Partnership on Transparency in the Paris Agreement (Transparency Partnership, 2018) could further help to disseminate waste-sector data collection practices to nations that are actively developing new data management systems in support of Paris Climate Agreement commitments.

Globally, many countries lack basic measurement tools such as scales to weigh incoming waste (UNEP, 2015; World Bank, 2012). Despite improvements in measuring and monitoring GHG emissions, substantial gaps remain in regional GHG budgets and input data quality often limits both bottom-up and top-down emissions estimates (Tian et al., 2016). Bottom-up measurement tools are critical to developing accurate inventories of waste amounts, types, and resultant emissions, particularly because of the noted disparities between top-down and measured, quality-assured bottom-up estimates of waste disposal such as that reported in the United States (Powell et al., 2016; Powell and Chertow, 2018) and China (Cai et al., 2018). As national-level measurement, reporting and verification (MRV) frameworks develop, facilitating and gathering basic waste data such as amount received, composition and geospatial information, a clearer picture of modern waste management would develop, enabling future cross-national comparisons. Data collection and reporting systems that leverage mobile applications may be preferable in light of the world's rapidly-increasing access to the internet and the technological convergence of mobile devices with standard personal computers (World Bank, 2016).

With regard to the NDCs specifically, details for the type of information to be included and the methods to be used for monitoring, reporting, and verification are expected to be developed by 2018 and formally adopted in 2020 (UN Framework Convention on Climate Change, 2015a). These guidelines will include elements related to tracking the impacts of commitments on emissions, sustainable development impacts, and progress made on implementation.

3.4. Waste sector mitigation and adaptation plans appear to be misaligned

In addition to mitigation actions, nearly all NDCs included adaptation plans in response to the call for such plans in the 20th Conference of the Parties in Lima, Peru (UN Framework Convention on Climate Change, 2017). Recent reviews show a sharp rise in adaptation planning across nations (Lesnikowski et al., 2016), with more rapid development in wealthy areas rather than the most vulnerable ones (Georgeson et al., 2016).

Adaptation plans were reviewed to identify the range of adaptation or resiliency planning at the country level corresponding to the waste sector. In contrast to the large number of countries incorporating the waste sector into mitigation plans, the analysis reveals waste management-related planning as largely absent from adaptation plans in NDCs. The gap between waste sector mitigation and adaptation planning raises the question of whether newly-planned waste infrastructure will appropriately consider climate change impacts that may come in the future. Future climate change scenarios depicting increased intensity and duration both of major storms, sea level rise, or increase in the frequency or intensity of wildfires have implications for disaster debris generation and as well as land use planning (Hay et al., 2015; Krasting et al., 2016; Mendelsohn et al., 2012). The quantity of waste produced following major storm events, ranging from material that substantially contributes to GHG emissions (municipal waste) to materials with no direct GHG impacts (soil and rocks), may be an order of magnitude larger than an area's normal annual waste production amount (Brown et al., 2011). As a result, the sizing and placement of disposal and waste processing facilities that can accommodate future storm events must be added to traditional planning metrics such as population growth and urban development.

4. Conclusions and limitations

This work represents a baseline analysis with which to compare future actions and progress in the waste sector. As nations update their NDCs, with additional details on specific actions and changes to future planning, developing an index may be warranted to quantify progress and to focus on remaining gaps, similar to indices developed to track national-level adaptation (Lesnikowski et al., 2016).

A limitation of the analysis here is the national scope of NDCs, which may miss important sub-national waste sector actions and efforts by municipalities, businesses, and non-profit organizations. The UNEP maintains a database of sub-national climate change mitigation activities on the Climate Initiatives Platform (Climate Initiatives Platform, 2018) A of 2018 the platform included 18 waste-related efforts spanning technical capacity development, implementation, and political dialogues. The five-year review and update period for NDCs may miss important, short-term dynamics associated with waste and recycling material supply chains, such as ongoing challenges associated with China's acceptance of certain recovered materials. Future work is needed that assesses waste-sector efforts by sub-national actors that can help to clarify the scope of waste-related climate mitigation efforts at different scales and by various actors.

A unique opportunity exists at the outset of the global push to reduce climate-forcing emissions to disseminate best waste data practices and reporting management systems to the global community, thus answering the call in many developing country NDCs for enhanced capacity building. Bringing forward best practices,

such as improved food waste management approaches (Chalak et al., 2016) and improved CH_4 collection at landfills would enhance the odds of successful follow-through on the Paris Climate Change Agreement. It also enables future comparative analyses and more accurate global reporting. Also, NDCs were found to primarily include measures to reduce direct carbon emissions, but indirect activities (such as waste prevention or reduction) could further contribute emission reductions for many nations. Taking such actions would help to curb the anticipated short-term warming effects of CH_4 emissions from waste in many rapidly urbanizing areas across the world which, in turn, raises the global climate change response trajectory.

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Author contributions

J.T.P. conceived the paper, analyzed the data, and wrote the manuscript; M.R.C. and D.C.E. provided substantial analytical guidance and writing contributions at all stages of the manuscript.

Competing financial interests

The authors declare no competing financial interests.

Appendix A. Supplementary material

Supplementary data associated with this article can be found, in the online version, at https://doi.org/10.1016/j.wasman.2018.09.008.

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